Analysis and Modeling of Ocean Acoustic Fluctuations and Moored Observations of Philippine Sea Sound-Speed Structure

John A. Colosi: PI
Department of Oceanography,
Naval Postgraduate School,
Monterey CA 93943
Ph: 831-656-3260, FAX: 831-656-2712, E-mail: jacolosi@nps.edu

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LONG-TERM GOALS

The long-term goals of this research are to understand the statistics of acoustic fields in both deep and shallow water ocean environments.

OBJECTIVES

The primary objective of this work is the development of accurate, and computationally efficient, reduced-physics acoustic propagation models for the prediction of the statistics of ocean acoustic signals in both shallow and deep water environments. Examples of acoustic field statistics of interest are mean intensity, coherence, and intensity variance. The focus here will be primarily on the Philippine Sea, and the SW06 site off the New Jersey coast, since these are the most recent and complete data sets. Reduced physics models are important to ocean acoustics not only because they are often computationally efficient but also because they elucidate what scales of the ocean can have the maximum impact on the acoustical field. This knowledge allows for more focused study on those oceanographic processes that will have large acoustical influences. Therefore centrally related to the primary objective of this research will be an effort to characterize ocean sound speed variability, and develop ocean models that can be easily assimilated into acoustic fluctuation calculations. In the Philippine Sea, models of eddies, internal tides, internal waves, and fine structure (spice) will be needed, while in the shallow water case a model of the random linear internal waves is lacking.

APPROACH

The approach taken here is to first test our reduced physics models against Monte Carlo simulation, and then once the scattering physics is understood, apply the models to observations. This approach was successfully used in developing a model for mode coupling caused by shallow water nonlinear internal waves (Colosi, 2008). Two different theoretical approaches will be considered. The first is a coupled mode technique originally described by Creamer (1996) and further developed by our group (Colosi and Morozov, 2009), and the second approach is a hybrid path-integral/geometric ray approximation for coherence properties along a time resolved wavefront.

In our analysis of ocean sound-speed structure we are utilizing observations from the 2009 Philippine Sea field trial and from the SW06 experiment. In these experiments moored seabird temperature,

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conductivity, and pressure sensors, as well as ADCPs were placed on multiple moorings giving vertical, temporal, as well as geographic information concerning ocean fluctuations. These data are being used to characterize internal tides, mesoscale eddies, stochastic Garret-Munk type internal waves, and intrusive finestructure (spice).

WORK COMPLETED

Work completed in the previous year has focused, by enlarge, on preparing for, and executing the Philippine Sea test in the spring of 2009, performing preliminary analysis of the oceanographic data, and Monte Carlo testing the coupled mode model for mean intensity in both deep and shallow water environments.

RESULTS

A. Coupled Mode Theory: Deep Water

Based on the work of Creamer (1996), Andrey Morozov and I have developed a coupled mode theory that can very accurately predict cross mode coherence functions which are used for important acoustical second moments like field coherence and mean intensity (Colosi and Morozov, 2009). The theory assumes small angle multiple forward scattering and that the Markov approximation is valid. Regarding the environment the theory assumes that the ocean sound speed structure is dominated by a random superposition of internal waves, like those described by the Garrett-Munk (GM) internal wave spectrum. For a fixed acoustic frequency, the range evolution of the cross mode coherence function $\left\langle a_n a_p^* \right\rangle(r)$ is given by

$$\frac{d}{dr}\left\langle a_n a_p^* \right\rangle = i(l_n - l_p^*)\left\langle a_n a_p^* \right\rangle - \sum_{m=1}^{N}\sum_{q=1}^{N}\left\langle a_q a_p^* \right\rangle I_{mn,qm} - \left\langle a_m a_q^* \right\rangle I_{mn,qp}^* - \left\langle a_q a_m^* \right\rangle I_{mp,qn} + \left\langle a_n a_q^* \right\rangle I_{mp,qm}^*$$

where $l_n = k_n + i\alpha_n$ is the complex mode wavenumber, and $I_{mn,pq}$ are scattering matrices which involved the spectrum of internal waves. In our work we have analytic forms for the scattering matrices, and since these matrices are independent of range the evolution equation is easily evaluated numerically. The cross mode coherence is central to predicting the mean intensity given by

$$\left\langle I(r,z) \right\rangle = \sum_{n=1}^{N}\sum_{p=1}^{N}\frac{\left\langle a_n a_p^*(r) \right\rangle}{r}\frac{\phi_n(z)\phi_p(z)}{\sqrt{k_n k_p}}$$

where $\phi_n(z)$ are the depth eigenfunctions of the unperturbed problem. Monte Carlo numerical simulations in a deep water environment with GM internal wave induced sound speed perturbations have been carried out and comparisons were made between the mean intensity computed from the simulations and predictions from the theory (Colosi and Morozov, 2009): These comparisons are shown in Fig. 1. In this case a 100-hz directed beam was simulated and the agreement between theory and Monte Carlo simulation is excellent both along the sound axis (upper panel) as well as in the beam shadow zone (lower panel).

B. Coupled Mode Theory: Shallow Water

The evolution equation for the cross mode coherence can also be used to better understand shallow water problems (Colosi, 2008). Taking an 80-m downward refracting shallow water waveguide with bottom attenuation of 0.5 dB/λ, bottom density of 1900 kg/m^3, bottom sound speed of 1650 m/s, Monte Carlo simulations with GM internal waves (j*=1) were computed and estimates of mean intensity from the simulation and the theory were compared. Figure 2 shows the comparison at 200 Hz for a point source at 70-m depth. The theory is seen to accurately represent the Monte Carlo simulation to within a fraction of a dB (nearly identical results are also seen at 400-Hz). Importantly the theory shows that cross mode coherences can decay quite rapidly in this shallow water environment (See Fig. 2 where mean intensity shows very little oscillations with range). The decay of cross mode coherences, and the phase randomization of the modes has important consequences regarding the interaction of sound with nonlinear internal solitary waves (ISW), as that interaction depends critically on the relative phases of modes at the ISW (Colosi, 2008; Preisig and Duda 1997). Also of keen importance is that the theory shows that internal wave scattering seen in the figures are strongly influenced by adiabatic influences as well as coupling.

C. Preliminary Analysis of Philippine Sea 2009 Oceanographic data

During the 2009 Philippine sea field test, 30 Seabird microcats and microtemps, as well as ADCP's were deployed on each of the source and receiver moorings in order to quantify the space time scales of sound-speed variability. Data were collected between April 5 and May 9, 2009 thus giving slightly over a one month record. The data have just recently been processed and some preliminary results are available. Figure 3 shows the frequency spectra of temperature measured on the receiver mooring; similar results were obtained on the source mooring. The spectra reveals

1. Energetic internal tides at semi-diurnal and diurnal frequencies,
2. A Garrett-Munk type internal wave continuum between the buoyancy and inertial frequencies, and
3. A spectral gap between the inertial frequency and the lower mesoscale frequencies.

One of the most intriguing aspects of these observations are the large internal tides which have a very coherent vertical structure indicative of a mode 1 dominance. Further analysis is being done to study the likely generation regions of the internal tides, and their temporal and vertical stability as a function of mode number.

A primary objective of these measurements was to isolate the sound speed variations cause by internal wave vertical displacement of isopycnals and those caused by temperature and salinity variations along isopycnals (finestructure, spice). Therefore on the receiver mooring, high precision pumped microcats were deployed to precisely monitor salinity variations so that isopycnal surfaces could be tracked over time. Figure 4 shows the observed depth and time variations of salinity along with some isopycnal contours: Where isopycnals cross salinity structure finestructure or spice is present. Strong finestructure is seen in the upper ocean between yeardays 105 and 120. Figure 5 shows the temperature and salinity variations (left panel) and sound speed variations (right panel) along the isopycnals. We are able to track an isopycnal to within 0.01 kg/m^3, and it is seen that fine structure is a significant part of the sound speed variation in the Philippine Sea.

IMPACT/APPLICATIONS

There are several implications of this work to the understanding of acoustic predictability. A short list of the major issues/impacts are given below.

1. Many observations and numerical studies have shown that internal wave induced sound speed perturbations have a large effect on mean intensity (transmission loss) in both shallow and deep water environments. The coupled mode theory developed by our group could conceivably be used as a Navy model for predicting low frequency mean TL.

2. The coupled mode theory developed by our group can also be ``trivially" modified to predict space and time coherences, which are important for ocean acoustic signal processing.

3. Broadband effects can also be treated in the coupled mode theory, but the computational issues may be significant.

4. The high quality Philippine Sea 2009 oceanographic data set will allow, for the first time, a definitive separation of internal-wave induced sound-speed perturbations and those caused by finestructure or spice. With this information ocean models could be constructed that separately treat internal waves and finestructure.

5. The Philippine Sea 2009 oceanographic data set will also allow the construction of a regional internal tide model: the relative important of internal tides to acoustic variability, however, is yet to be determined.

TRANSITIONS

None

RELATED PROJECTS

None

REFERENCES

1. Colosi, J.A., ``Acoustic mode coupling induced by shallow water nonlinear internal waves: Sensitivity to environmental conditions and space-time scales of internal waves'', J. Acoust. Soc. Am., 124(3), pp 1452-1464, 2008.

2. Colosi, J.A. and A.K. Morozov, ``Statistics of normal mode amplitudes in an ocean with random sound speed perturbations: Cross mode coherence and mean intensity'', J. Acoust. Soc. Am., 126(3), pp, 1026-1035, 2009

3. Creamer, D. `` Scintillating shallow water waveguides'', J. Acoust. Soc. Am., 09, pp2825-2838 (1996).

4. Preisig, J. and T. Duda, ``Coupled acoustic mode propagation through continental shelf internal solitary waves", IEEE J. Oceanic Eng., 22, pp256-269.

RECENT PUBLICATIONS

1. Colosi, J.A., ``Acoustic mode coupling induced by shallow water nonlinear internal waves: Sensitivity to environmental conditions and space-time scales of internal waves'', J. Acoust. Soc. Am., 124(3), pp 1452-1464, 2008.

2. Flatte, S., and J. Colosi, ``Anisotropy of the wavefront distortion for acoustic pulse propagation through ocean sound-speed fluctuations: A ray perspective'', IEEE J. Oceanic Eng, V33(4), pp477-488, 2008.

3. Colosi, J.A., J. Xu, M.A. Dzieciuch, P. Worcester, B. Howe, J. Mercer, and B. Spindel, ``Temporal and vertical scales of acoustic fluctuations from 75-Hz, broadband transmissions to 87-km range in the eastern North Pacific Ocean'', 126(3), pp1069-1083, 2009.

4. Mercer, J., J. Colosi, B. Howe, M. Dzieciuch, R. Stephen, and P. Worcester, ``LOAPEX: The Long Range Acoustic Propagation Experiment'', IEEE J. Oceanic Eng., 34(1), pp1-11, 2009.

5. Stephen, R., M. Dzieciuch, P. Worcester, R. Andrew, B. Howe, J. Mercer, and J. Colosi, ``Deep shadow zone arrivals on the seafloor'', J. Acoust. Soc. Am., 126(2), pp599-606, 2009.

6. Colosi, J.A. and A.K. Morozov, ``Statistics of normal mode amplitudes in an ocean with random sound speed perturbations: Cross mode coherence and mean intensity'', J. Acoust. Soc. Am., 126(3), pp, 1026-1035, 2009

PATENTS

None

HONORS/AWARDS/PRIZES

A. B. Wood Medal for "significant contributions to the understanding of acoustic scattering by internal waves in long-range propagation".

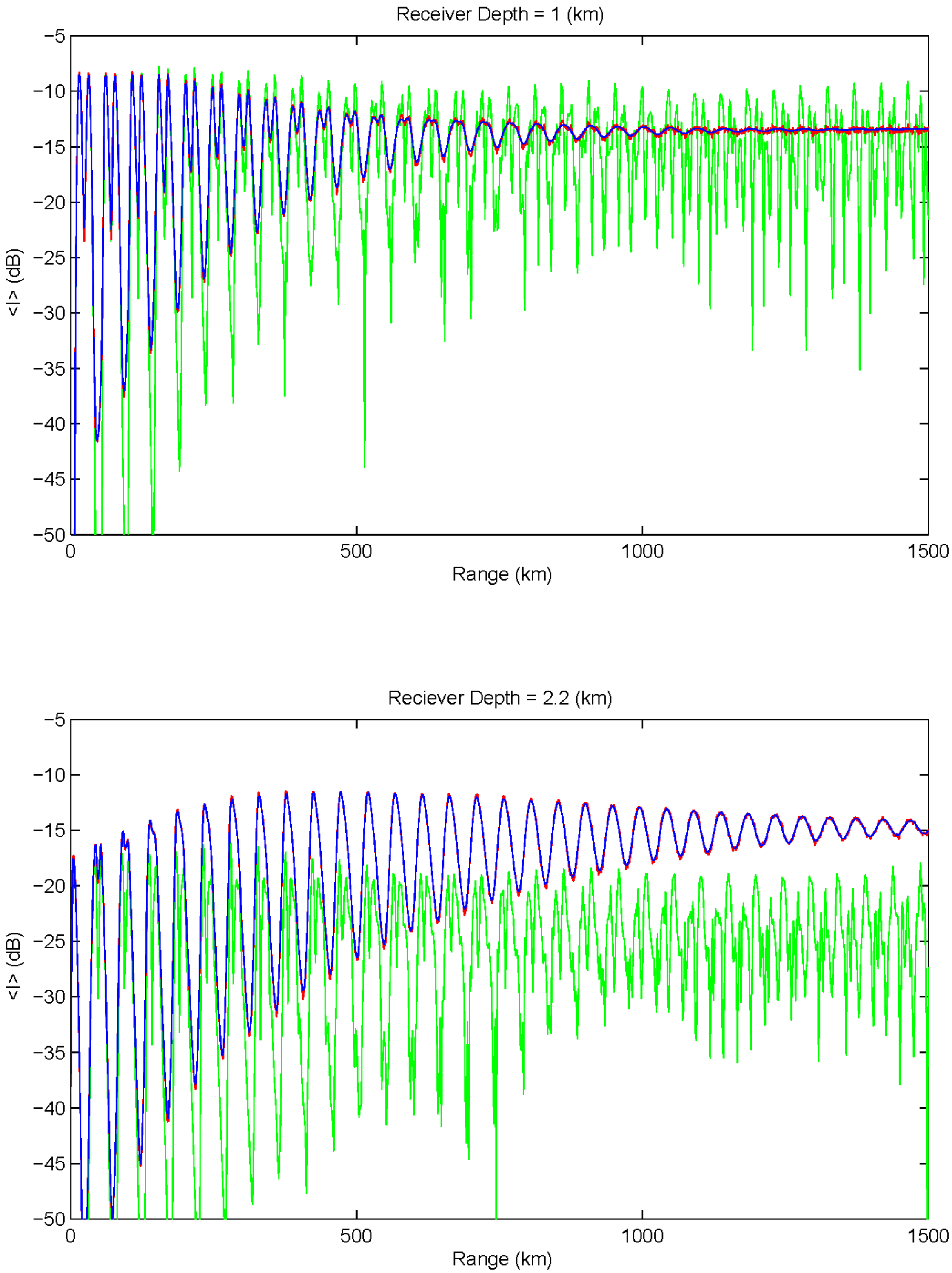

Figure 1: Monte Carlo Simulation (Red) and theory prediction (Blue) of mean sound intensity for 100 Hz sound propagation through random fields of GM internal waves. In this example a directed acoustical beam at 2-km depth is modeled, and the receiver depths are 1.0 and 2.2 km. The unperturbed sound intensity is plotted in green for reference. Cylindrical spreading has been removed.

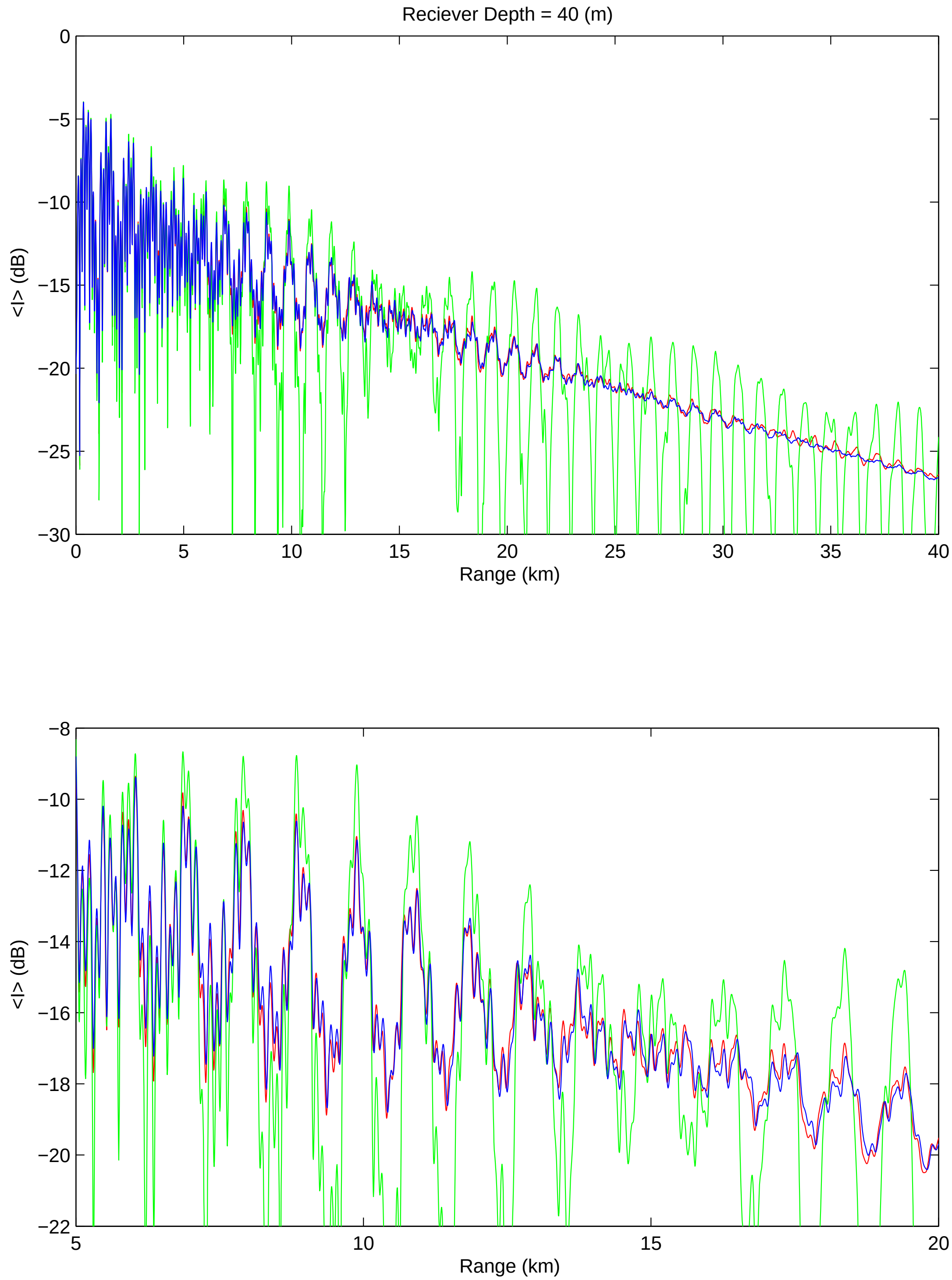

Figure 2: Monte Carlo Simulation (Red) and theory prediction (Blue) of mean sound intensity for 200 Hz sound propagation in shallow water through random fields of GM internal waves. The unperturbed intensity is shown in green. The upper panel shows the mean intensity for a receiver at 40-m depth, out to 40-km range. The lower panel shows an expanded view of the range 5-20 km. Cylindrical spreading effects have been removed.

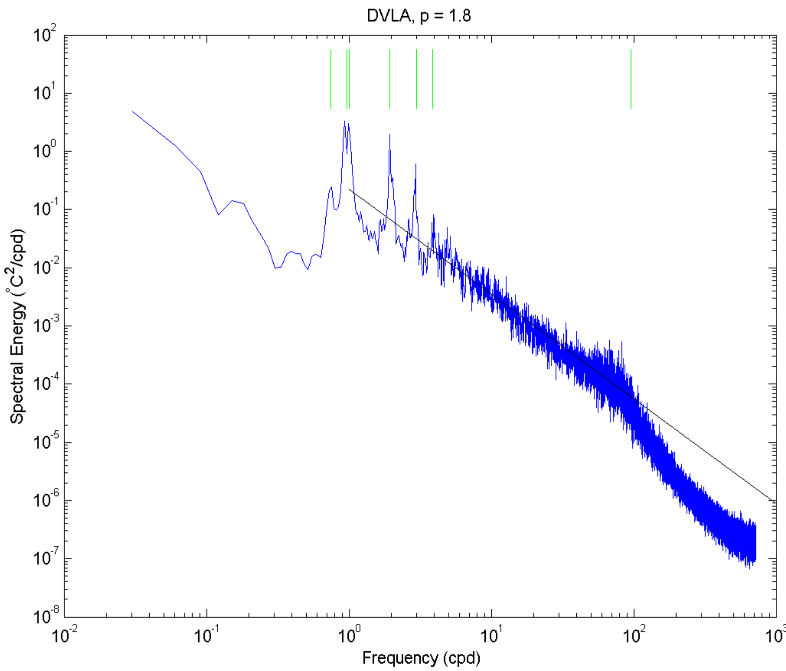

Figure 3: Frequency spectrum of temperature fluctuations measured at the receiver array during the 2009 Philippine Sea field test. The sloped black line shows a power law of $\omega^{-1.8}$.

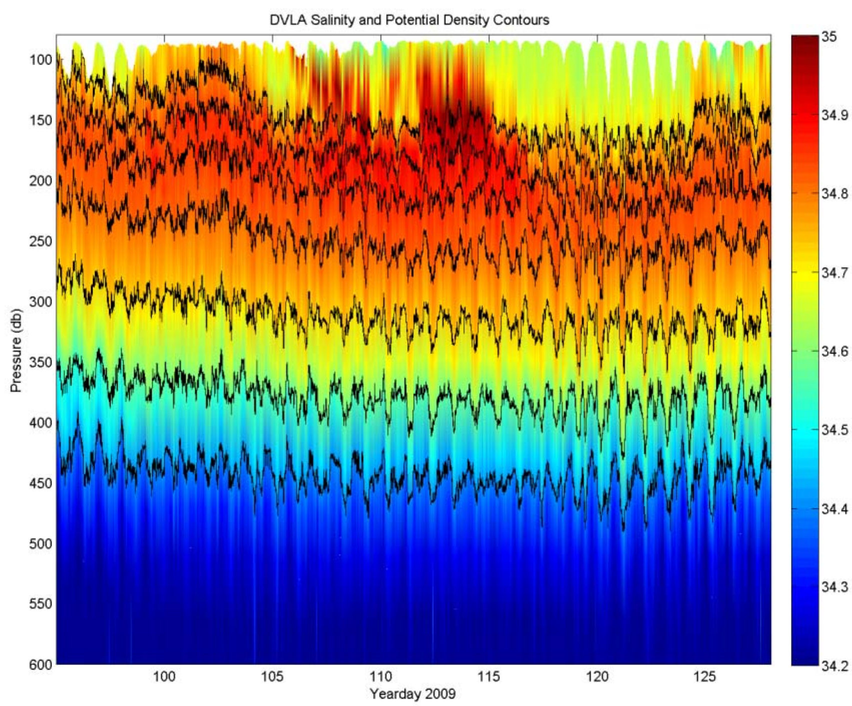

Figure 4: Salinity fluctuations observed on the Philippine Sea 2009 receiver mooring, and isopycnal contours of 1024 to 1026 kg/m³ in increments of 1/3 kg/m³. Isopycnals fluctuate in depth due to internal waves, and variations of salinity along an isopycnal are due to intrusive finestructure.

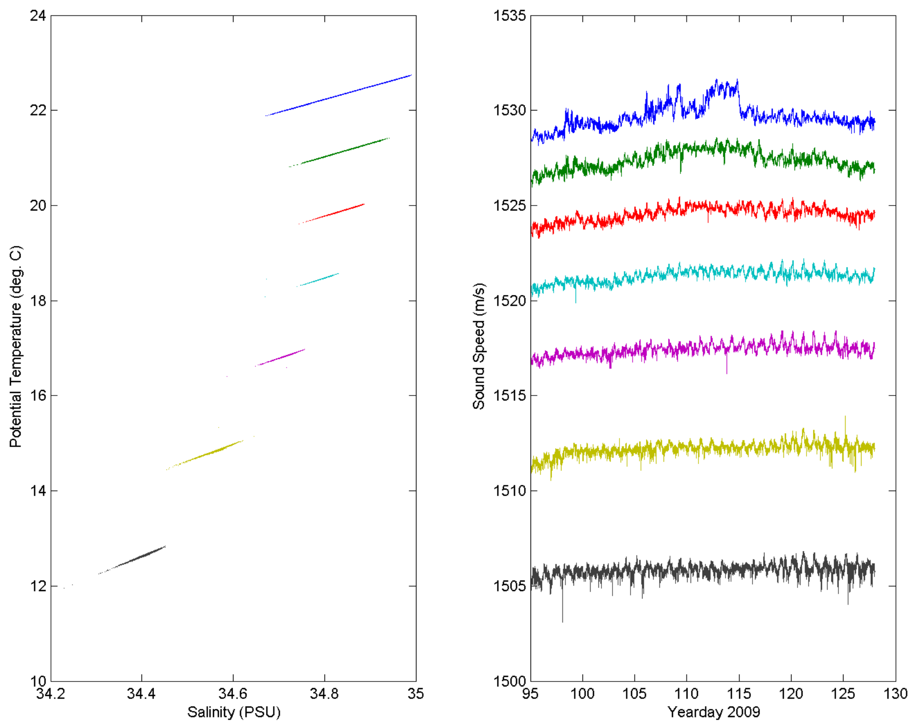

Figure 5: Variation of temperature and salinity along seven isopycnals (left), and sound-speed variations as a function of time along the same seven isopycnals (right).